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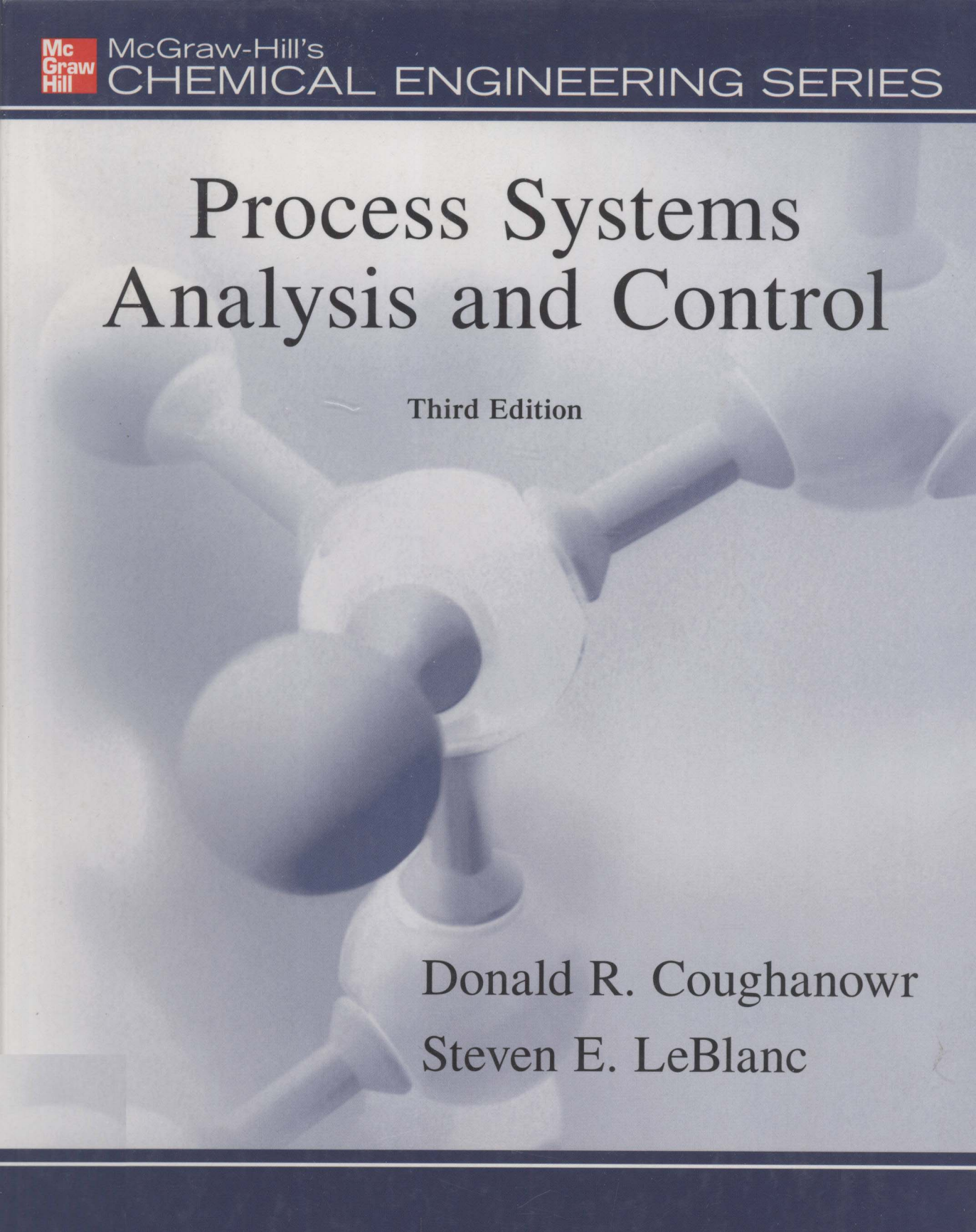
Process Systems Analysis and Control

Third Edition



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PROCESS SYSTEMS ANALYSIS AND CONTROL

THIRD EDITION

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PROCESS SYSTEMS ANALYSIS AND CONTROL

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The Founding of a Discipline:
The McGraw-Hill Companies, Inc. Series in Chemical Engineering

Over 80 years ago, 15 prominent chemical engineers met in New York to plan a continuing literature for their rapidly growing profession. From industry came such pioneer practitioners as Leo H. Baekeland, Arthur D. Little, Charles L. Reese, John V. N. Dorr, M. C. Whitaker, and R. S. McBride. From the universities came such eminent educators as William H. Walker, Alfred H. White, D. D. Jackson, J. H. James, Warren K. Lewis, and Harry A. Curtis. H. C. Parmlee, then editor of *Chemical and Metallurgical Engineering,* served as chairman and was joined subsequently by S. D. Kirkpatrick as consulting editor.

After several meetings, this committee submitted its report to the McGraw-Hill Book Company in September 1925. In the report were detailed specifications for a correlated series of more than a dozen texts and reference books which became the McGraw-Hill Series in Chemical Engineering—and in turn became the cornerstone of the chemical engineering curricula.

From this beginning, a series of texts has evolved, surpassing the scope and longevity envisioned by the founding Editorial Board. The McGraw-Hill Series in Chemical Engineering stands as a unique historical record of the development of chemical engineering education and practice. In the series one finds milestones of the subject's evolution: industrial chemistry, stoichiometry, unit operations and processes, thermodynamics, kinetics, and transfer operations.

Textbooks such as McCabe et al., *Unit Operations of Chemical Engineering,* Smith et al., *Introduction to Chemical Engineering Thermodynamics,* and Peters et al., *Plant Design and Economics for Chemical Engineers* have taught to generations of students the principles that are key to success in chemical engineering.

Chemical engineering is a dynamic profession, and its literature continues to grow. McGraw-Hill, with its in-house editors and consulting editors Eduardo Glandt (Dean, University of Pennsylvania), Michael Klein (Dean, Rutgers University), and Thomas Edgar (Professor, University of Texas at Austin), remains committed to a publishing policy that will serve the needs of the global chemical engineering profession throughout the years to come.

Dedication

For Molly, my children, and grandchildren . . .

PREFACE TO THE THIRD EDITION

It has been over 17 years since the second edition of this book was published. The second edition, which was written by Dr. Donald R. Coughanowr in 1991, contained many changes and new topics to bring the book up to date at the time of publication. The third edition has been a number of years in the making. I would like to thank Dr. Coughanowr for the opportunity to work on this project and help update this excellent work, which he first published in 1965 with Dr. Lowell B. Koppel. As an undergraduate, I learned process control from the first edition of this text over 30 years ago. It was an excellent book then, and it still is. I've used a number of other books over the years as a student and as a professor, but I kept coming back to this one. I felt that it was the best book to learn from. Is it an all-encompassing, totally comprehensive process dynamics and control book? No, but it is not intended to be. It is a clearly written book that is geared toward students in a first process dynamics and control course. Many control books on the market contain more material than one could ever hope to cover in a standard undergraduate semester-long class. They can be overwhelming and difficult to learn from. I have always felt that one of the strengths of this book, from both the student's and professor's point of view, was the relatively short, easy-to-read chapters that can be covered in one to two lectures. An additional strength of this text has been its unique ability to be a teaching and learning text. I hope that in this current revision, I have been able to retain that style and flavor, while introducing some new material and examples to update the text.

OBJECTIVES AND USES OF THE TEXT

This text is intended for use in an introductory one-semester-long undergraduate process dynamics and control course. It is intended to be not a comprehensive treatise on process control, but rather a textbook that provides students with the tools to learn the basic material and be in a position to continue their studies in the area if they so choose. Students are expected to have a background in mathematics through differential equations, material and energy balance concepts, and unit operations. After the first 13 chapters, the instructor may select from the remaining chapters to fit a course of particular duration and scope. A typical one-semester 15-week course, for example, may include Chapters 1 through 19 and 26.

Features of the third edition

- A capsule summary of the important points at the end of each chapter
- Restructuring of the initial chapters to reduce the impression that students frequently have regarding control classes—that this is just another mathematics course disguised as an engineering course
- Integration of MATLAB,® Simulink,® and Excel throughout the text:
  - To reduce the tedium of solving problems so that students may concentrate more on the concepts of dynamics and control and not get bogged down in the mathematical complexities of each problem

- To give students the tools to be able to ask (and more easily answer) "what if . . .?" type of questions
- To allow students to explore more difficult problems than would otherwise be possible in the time available for the course material

ACKNOWLEDGMENTS

We would like to thank the following reviewers of the third edition for their helpful comments and suggestions: Thomas F. Edgar, University of Texas–Austin; John Erjavec, University of North Dakota; Duane Johnson, University of Alabama; Costas Maranas, Penn State University; Michael Nikolaou, University of Houston; F. Joseph Schork, Georgia Institute of Technology; Delmar Timm, University of Nebraska; and William A. Weigand, University of Maryland. We especially acknowledge the helpful suggestions from Susan Montgomery of the University of Michigan and thank her for her thoroughness and useful comments to help make the text more student-friendly.

I would like to thank McGraw-Hill for having confidence in this project and providing the opportunity to revise and update the text. Special thanks go to Lorraine Buczek, Developmental Editor, and Melissa Leick, Project Manager, for their help in the final stages of this revision.

I would also like to thank my students and my University of Toledo colleague Sasidhar Varanasi for his help in using manuscript drafts when he taught the Process Control course to "field-test" the revisions. I am also grateful to my friend and colleague Dean Nagi Naganathan, of the College of Engineering at the University of Toledo, for his general support and his willingness to allow me the time required to complete this work. I especially want to thank my wife, Molly, for her love and continuing encouragement and support over the course of the writing and revising.

Dr. Steven E. LeBlanc
University of Toledo

RESOURCES FOR INSTRUCTORS AND STUDENTS:

For instructors, the solutions to the end-of-chapter problems are available at the text's website: www.mhhe.com/coughanowr-leblanc

ELECTRONIC TEXTBOOK OPTIONS

This text is offered through CourseSmart for both instructors and students. CourseSmart is an online browser where students can purchase access to this and other McGraw-Hill textbooks in a digital format. Through their browser, students can access the complete text online for one year at almost half the cost of a traditional text. Purchasing the eTextbook also allows students to take advantage of CourseSmart's Web tools for learning, which include full text search, notes and highlighting, and e-mail tools for sharing notes between classmates. To learn more about CourseSmart options, contact your sales representative or visit www.CourseSmart.com.

HISTORY OF PROCESS SYSTEMS ANALYSIS AND CONTROL (FROM THE SECOND EDITION PREFACE)

Since the first edition of this book was published in 1965, many changes have taken place in process control. Nearly all undergraduate students in chemical engineering are now required to take a course in process dynamics and control. The purpose of this book is to take the student from the basic mathematics to a variety of design applications in a clear, concise manner.

The most significant change since the first edition is the use of the digital computer in complex problem solving and in process control instrumentation. However, the fundamentals of process control, which remain the same, must be acquired before one can appreciate the advanced topics of control.

In its present form, this book represents a major revision of the first edition. The material for this book evolved from courses taught at Purdue University and Drexel University. The first 17 chapters on fundamentals are quite close to the first 20 chapters of the first edition. The remaining 18 chapters contain many new topics, which were considered very advanced when the first edition was published.

Knowledge of calculus, unit operations, and complex numbers is presumed on the part of the student. In certain later chapters, more advanced mathematical preparation is useful. Some examples would include partial differential equations in Chap. 21, linear algebra in Chaps. 28 through 30, and Fourier series in Chap. 33.

Analog computation and pneumatic controllers in the first edition have been replaced by digital computation and microprocessor-based controllers in Chaps. 34 and 35. The student should be assigned material from these chapters at the appropriate time in the development of the fundamentals. For example, the transient response for a system containing a transport lag can be obtained easily only with the use of computer simulation of the transport lag. Some of the software now available for solving control problems should be available to the student; such software is described in Chap. 34. To understand the operation of modern microprocessor-based controllers, the student should have hands-on experience with these instruments in a laboratory.

Chapter 1 is intended to meet one of the problems consistently faced in presenting this material to chemical engineering students, that is, one of perspective. The methods of analysis used in the control area are so different from the previous experiences of students that the material comes to be regarded as a sequence of special mathematical techniques, rather than an integrated design approach to a class of real and practically significant industrial problems. Therefore, this chapter presents an overall, albeit superficial, look at a simple control system design problem. The body of the text covers the following topics: Laplace transforms, Chaps 2. to 4; transfer functions and responses of open-loop systems, Chaps. 5 to 8; basic techniques of closed-loop control, Chaps. 9 to 13; stability, Chap. 14; root locus methods, Chap. 15; frequency response methods and design, Chaps. 16 and 17; advanced control strategies (cascade, feedforward, Smith predictor, internal model control), Chap. 18; controller tuning and

process identification, Chap. 19; control valves, Chap. 20; advanced process dynamics, Chap. 21; sampled-data control, Chaps. 22 to 27; state-space methods and multivariable control, Chaps. 28 to 30; nonlinear control, Chaps. 31 to 33; digital computer simulation, Chap. 34; microprocessor-based controllers, Chap. 35.

It has been my experience that the book covers sufficient material for a one-semester (15-week) undergraduate course and an elective undergraduate course or part of a graduate course. In a lecture course meeting 3 hours per week during a 10-week term, I have covered the following chapters: 1 to 10, 12 to 14, 16, 17, 20, 34, and 35.

After the first 14 chapters, the instructor may select the remaining chapters to fit a course of particular duration and scope. The chapters on the more advanced topics are written in a logical order; however, some can be skipped without creating a gap in understanding.

I gratefully acknowledge the support and encouragement of the Drexel University Department of Chemical Engineering for fostering the evolution of this text in its curriculum and for providing clerical staff and supplies for several editions of class notes. I want to acknowledge Dr. Lowell B. Koppel's important contribution as coauthor of the first edition of this book. I also want to thank my colleague Dr. Rajakannu Mutharasan for his most helpful discussions and suggestions and for his sharing of some of the new problems. For her assistance in typing, I want to thank Dorothy Porter. Helpful suggestions were also provided by Drexel students, in particular Russell Anderson, Joseph Hahn, and Barbara Hayden. I also want to thank my wife Effie for helping me check the page proofs by reading to me the manuscript, the subject matter of which is far removed from her specialty of Greek and Latin.

McGraw-Hill and I would like to thank Ali Cinar, Illinois Institute of Technology; Joshua S. Dranoff, Northwestern University; H. R. Heichelheim, Texas Tech University; and James H. McMicking, Wayne State University, for their many helpful comments and suggestions in reviewing this second edition.

Dr. Donald R. Coughanowr

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ABOUT THE AUTHORS

Steven E. LeBlanc is Associate Dean for Academic Affairs and professor of chemical engineering at the University of Toledo. He received a B.S. degree in chemical engineering from the University of Toledo and his M.S. and Ph.D. in chemical engineering from the University of Michigan. He joined the faculty at the University of Toledo in 1980. He served as the department chair for the Department of Chemical and Environmental Engineering from 1993 to 2003, when he became an Associate Dean in the College of Engineering.

Dr. LeBlanc's industrial experience includes power plant process system design and review for Toledo Edison Company (now a division of First Energy). He has taught the Process Dynamics and Control course numerous times, and was responsible for a major revamp of laboratory activities associated with the course.

He is a member of the American Institute of Chemical Engineers (AIChE) and the American Society for Engineering Education (ASEE). He has served as an ABET chemical engineering program evaluator for AIChE since 1998. He chaired the national ASEE Chemical Engineering Education Division and cochaired the 2007 ASEE Chemical Engineering Summer School for Faculty. He coauthored and judged the 1992 AIChE Senior Design Project competition. He is also coauthor of a textbook on *Strategies for Creative Problem Solving* with H. Scott Fogler of the University of Michigan.

Donald R. Coughanowr is Emeritus Professor of Chemical Engineering at Drexel University. In 1991 he wrote the second edition of *Process Systems Analysis and Control* which contained many changes and new topics in order to bring the book up to date at the time of publication. He received a Ph.D. in chemical engineering from the University of Illinois in 1956, an M.S. degree in chemical engineering from the University of Pennsylvania in 1951, and a B.S. degree in chemical engineering from the Rose-Hulman Institute of Technology in 1949. He joined the faculty at Drexel University in 1967 as department head, a position he held until 1988. Before going to Drexel, he was a faculty member of the School of Chemical Engineering at Purdue University for 11 years.

At Drexel and Purdue he taught a wide variety of courses, which include material and energy balances, thermodynamics, unit operations, transport phenomena, petroleum refinery engineering, environmental engineering, chemical engineering laboratory, applied mathematics, and process dynamics and control. At Purdue,

he developed a new course and laboratory in process control and collaborated with Dr. Lowell B. Koppel on the writing of the first edition of *Process Systems Analysis and Control.*

His research interests included environmental engineering, diffusion with chemical reaction, and process dynamics and control. Much of his research in control emphasized the development and evaluation of new control algorithms for the processes that cannot be controlled easily by conventional control; some of the areas investigated were time-optimal control, adaptive pH control, direct digital control, and batch control of fermentors. He reported on his research in numerous publications and received support for research projects from the National Science Foundation and industry. He spent sabbatical leaves teaching and writing at Case-Western Reserve University, the Swiss Federal Institute, the University of Canterbury, the University of New South Wales, the University of Queensland, and Lehigh University.

Dr. Coughanowr's industrial experience included process design and pilot plant at Standard Oil Co. (Indiana) and summer employment at Electronic Associates and Dow Chemical Company.

He is a member of the American Institute of Chemical Engineers. He has served the AIChE by participating in accreditation visits to departments of chemical engineering for ABET and by chairing sessions of the Department Heads Forum at the annual meetings of AIChE.

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